INVESTIGATION OF ORTHOPYROXENE DIVERSITY IN HOWARDITE METEORITES.

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Introduction: The howardite, eucrite and diogenite (HED) family of meteorites is considered to originate from the asteroid 4-Vesta [1]. Howardites are polymict breccias made mostly of diogenitic and eucritic debris [2], and have recently been divided into two types: regolithic and fragmental [3]. Regolithic howardites have higher noble gas contents due to solar wind exposure, have a greater abundance of impact-produced glass, are richer in siderophile elements, e.g. Ni, and may preferentially have a mixing ratio of eucrite to diogenite of ~2:1 [3]. The hypothesis is that these characteristics are a result of originating from an ancient, well-mixed regolith [3]. Fragmental howardites, by contract, show less evidence of regolithic processing and are suggested to have originated in more recently formed impact ejecta [3]. Our work aims to evaluate this hypothesis.

We have examined the compositional variations of orthopyroxene (diogenite) clasts within eight howardites. We posited that because regolithic howardites sampled a wider range of the asteroid surface, they would contain orthopyroxene fragments with wider ranges in incompatible element contents than would fragmental howardites that sampled fewer diogenitic source rocks. One purpose of developing an additional method to differentiate regolithic and fragmental howardites is to aid in interpretation of data expected from the Dawn mission to 4-Vesta. The Dawn analyses will be of the regolith layers, making an understanding of regolithic meteorites and the processes by which they were formed an important constraint on understanding Dawn data.

Methods: All analyses were done at JSC. Thick sections (150 μm) from eight howardites (Table 1) were studied. Companion thin sections were examined using optical methods. Petrographic descriptions were recorded and integrated with XRF bulk analysis data [4]. The sections were imaged using a 5910LV scanning electron microscope, and energy dispersive spectroscopy data were used to select orthopyroxene targets for electron microprobe analysis (EMPA). EMPA data sets for each meteorite were taken using a Cameca SX100 electron microprobe. Grain compositions were determined by averaging several data points. We will consider only grains with ≤5 mole% Wo which are more directly comparable to diogenitic pyroxenes. A subset of orthopyroxene grains was analyzed for a suit of lithophile elements by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) using a New Wave UP-193 laser mated to a Thermo Fisher Element2-XR ICP-MS. We will give our preliminary interpretation based on these data and work by our colleagues [5].

Results: Table 1 gives a synopsis of our petrographic observations and bulk compositions [4], including classification as possible regolithic subtype under criteria of high Ni and Al_2O_3 between 8-9 wt% [c.f. 3], and a set of petrologic criteria we are evaluating as indicators of regolithic history [5]. We will focus our discussion on four of the howardites; PCA 02066 which we suggest is regolithic, CRE 01400 and LAP 04838 which are not, and QUE 97001 which may be regolithic (Table 1).

Table 1: Petrographic/Bulk Compositional Synopsis.

meteorite	clast size	clast shape	reworked clasts?	impact melts?	chondritic clasts?	euc / dio	Ni (μg/g)	Al_2O_3 (wt%)	regolithic?
CRE 01400	coarse	subangular	no	no	no	25/75	24	5.1	no
EET 87513	medium/fine	subangular	maybe	yes	no	65/35	142	9.0	maybe
EET 99408	medium/fine	rounded	yes	yes	no	80/20	224	11.5	maybe
LAP 04838	medium/coarse	subangular	no	yes	no	85/15	45	10.9	no
PCA 02066	medium/fine	angular	yes	no	no	30/70	792	8.0	yes
PRA 04401	coarse	angular	no	yes	yes	50/50	4440	4.2	no
QUE 97001	medium	subangular	no	yes	no	30/70	262	5.5	maybe
SAN 03472	medium	subangular	no	yes	no	65/35	262	10.2	maybe

On Al vs. Ti plots (Fig. 1), the candidate regolithic howardite, PCA 02066 shows greater data dispersion than do those we consider to be fragmental howardites (CRE 01400 and LAP 04838). The latter show data dispersions similar to that of the diogenite EETA79002, a genomict breccia composed of material from ≥3 closely related diogenitic plutons [6]. QUE 97001, which is possibly regolithic, shows greater dispersion in Al-Ti than the fragmental howardites, but slightly less than shown by PCA 02066. On Hf vs. Ti and Hf vs. Wo% plots (Fig. 2) PCA 02066 again shows greater compositional dispersion than do the fragmental howardites, with QUE 97001 being intermediate.

Discussion: The diversity of orthopyroxene grain compositions in each meteorite shows some correspondence with the regolithic character determined from petrographic and bulk compositional study. For example, orthopyroxenes in CRE 01400 and LAP 04838 show little dispersion in the minor elements Al and Ti and have ranges similar to those of diogenite EETA79002 (Fig. 1). They also show more limited ranges in orthopyroxene incompatible trace element contents (Fig. 2). This supports our hypothesis that fragmental howardites may contain clasts from a more limited number of diogenitic plutons. Candidate regolithic howardite PCA 02066 shows a wide diversity of orthopyroxene incompatible element contents (Figs. 1, 2), suggesting that a greater number of diogenitic plutons is represented in

this breccia. QUE 97001 is possibly regolithic based on our petrographic evaluation. Pyroxene compositions in it show more diversity than for the candidate fragmental howardites, but less than in PCA 02066. Coupling our pyroxene data with the petrographic descriptions (Table 1), those samples that have more rounded, smaller clasts correspond to regolithic environments. Samples with larger and more angular clasts did not experience as much regolithic activity.

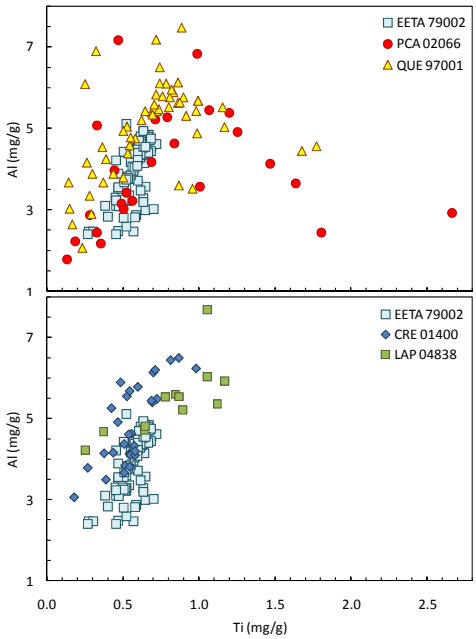
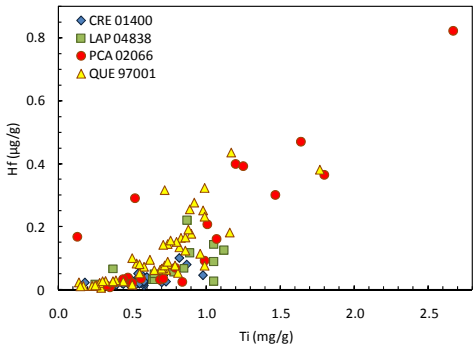
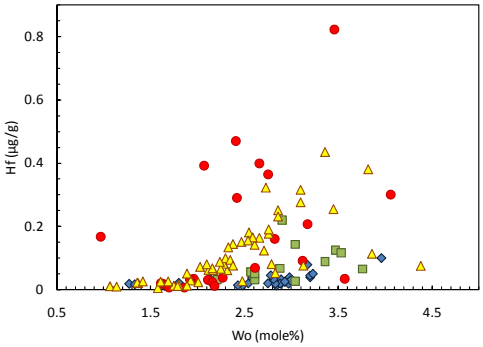


Figure 1: Al vs. Ti of orthopyroxene for select howardites compared to diogenite EETA79002 [6].

Our colleagues' preliminary work on noble gas contents of the howardites show that the scenario we just presented is too simple. The Ne isotopic composition shows that PCA 02066 is dominated by Ne produced by galactic cosmic ray interactions, with little or no evidence of solar wind or solar energetic particle implanted Ne that would be expected for regolithic howardites [5].

Figure 2: Hf vs. Ti and Hf vs. Wo component of orthopyroxene for select howardites.





The presence of chondritic material, evidenced by enhanced siderophile element contents, is one potential indicator of a regolithic sample [3]. However, high siderophile element contents are not conclusive evidence. Case in point is PRA 04401, which has a very high Ni content (Table 1) [4]. This meteorite contains abundant, mm-sized angular chondritic clasts, estimated at ~35 wt% from the bulk analysis and 60-70 vol% based on a thin section modal estimate [4, 7]. The clasts have remained large, angular and concentrated in the howardite. This is an indication that the breccia did not undergo the extensive regolith gardening, which would have reduced the clast size and angularity, and dispersed the chondritic material. Orthopyroxene compositions of PRA 04401 (not plotted) have significant diversity in Ti, Al and Hf similar to what we observe for PCA 02066 and QUE 97001 and much more than typically seen in individual diogenites. This suggests that it contains orthopyroxene debris from several diogenitic plutons and may be regolithic.

Conclusions: PCA 02066 exhibits regolithic qualities with a variety of diogenite grains in a fine- to medium-grained matrix. Clasts in the sample are rounded and diverse in chemical composition, impact melt clasts are common, and this meteorite has a high Ni content (Table 1) [4]. PCA 02066 exhibits evidence of regolith gardening. Thus far, it appears that orthopyroxene compositional variation may provide an additional tool for evaluating the regolithic character of a howardite.

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